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Discussion

Comments on "Coastal mangrove forests mitigated tsunami" by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601−606]

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In a paper published recently in the journal *Estuarine, Coastal and Shelf Science*, Kathiresan and Rajendran (2005) present a "case study on the mitigating effect of mangroves on human lives against tsunami." They use simple linear regressions to identify factors responsible for differences in per-capita mortality between 18 coastal hamlets in Tamil Nadu, India in the wake of the Boxing Day Tsunami of 2004. They find that mortality is significantly associated with hamlet elevation, distance from sea and the area of coastal frontage given to vegetation. From these analyses, they primarily conclude that "human habitation should be encouraged … behind dense mangroves and or other coastal vegetation." This is a potentially important finding and, if true, could save many lives in future. However, we have found several fundamental errors in their statistical analysis that undermine their main conclusion. We discuss these issues below.

First, Kathiresan and Rajendran (2005) individually regressed potential predictor variables against the dependent variable, per-capita hamlet mortality, whose variation it was they sought to explain. This resulted in regression equations that, surprisingly, assign functional dependence of large-scale physiographic variables such as topography and degree of forestation to human deaths.

Second, as data based on counts, the dependent variable, mortality, is likely to be distributed in Poisson fashion, rather than be normally distributed as required by the parametric tests used by Kathiresan and Rajendran (2005). We tested this assumption using a series of fractional exponential transformations to maximise the χ^2-distributed statistic K^2 in a D'Agostino−Pearson test as recommended by Zar (1999). Untransformed variates deviated considerably from normality ($K^2 = 4.835$, $n = 18$, df $= 2$, $p = 0.0891$). A transformation of $y_i^{0.47}$ minimised the asymmetry and mesokurtosis of the variates ($K^2 = 1.390$, $p = 0.499$) and, hence, is preferred to that of unit power.

Most importantly, however, Kathiresan and Rajendran (2005), in applying multiple independent tests, failed to account for potential covariation between the independent variables. For example, after appropriately transforming the area of coastal vegetation V fronting hamlets, this variable was significantly positively associated with a hamlet's distance D from the sea ($V = 0.686 + 0.913D$, $R^2 = 0.367$, $p = 0.00771$) and elevation E above sea level ($V = 0.525 + 0.553E$, $R^2 = 0.276$, $p = 0.0251$). Consequently, how much of the variation in mortality ascribed by the authors as due to vegetation is, in fact, driven by the latter variable's obvious dependence on the two physiographic factors?

To address this issue, we performed stepwise regressions on the exponentially transformed mortality data using the variables distance from sea, elevation above sea level, and area of vegetation. This type of analysis statistically controls for the potentially confounding effects of covariation between the predictor variables. That is, partial regression can assess the degree to which vegetation is associated with mortality independent of changes in distance or elevation. This analysis is summarised in Table 1a, which shows the effect of sequentially adding each predictor. Distance from sea explains nearly 50% of variation in mortality. Adding elevation explains

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Table 1
A summary of the results of a series of stepwise regressions on the exponentially transformed mortality data and loss of wealth

Dependent variable	Independent variables	R^2	F_S	P
(a) Mortality	Distance from sea	0.492	15.476	0.00119
	Elevation	0.863	40.602	0.0000125
	Vegetation area	0.863	0.0571	0.825
(b) Mortality	Distance from sea	0.492	15.476	0.00119
	Elevation	0.863	40.602	0.0000125
	Dense vegetation	0.864	0.0442	0.847
(c) Loss of wealth	Distance from sea	0.614	25.533	0.000118
	Elevation	0.615	0.00576	0.931
	Vegetation area	0.624	0.309	0.587
(d) Loss of wealth	Distance from sea	0.614	25.533	0.000118
	Elevation	0.615	0.00576	0.931
	Dense vegetation	0.663	1.846	0.196

an additional 37%, significantly increasing the amount of explained variation to 87%. After these two variables, vegetation area on its own then provides less than a 1% increase in explanatory power that we cannot distinguish from chance at even very liberal probabilities of a Type I error. We conclude, therefore, that the apparent association of vegetation area on mortality is in fact due to a tendency for more vegetation to occur at higher elevations and, not surprisingly, to the greater potential areal extent of vegetation given more available area fronting a hamlet. In other words, given hamlets of equal elevation and distance from the sea, differences in vegetation area did not mitigate human mortality caused by the tsunami.

Repeating the analyses, using this time the exponentially transformed per-capita loss of wealth as the dependent variable, obtains similar results, with the exception that only distance inland is significant, explaining 61% of variation in wealth lost, while elevation and vegetation area together only explain an additional 6.5% (Table 1c).

One possible reason for these results is that there is considerable variation in the ability of different types of vegetation to mitigate disaster. Combining together areas of sparse and thick vegetation could disguise an otherwise potentially important ameliorating effect of the latter on human mortality. Indeed, Kathiresan and Rajendran (2005) observed that some hamlets appeared to have escaped high mortality because these centres were "…protected with dense vegetation…." (p. 604), though they did not address this possibility statistically. Hence, to test this idea, as an alternative to vegetation area, we used a binary dummy variable for the presence of dense stands of mangroves, *Casuarina* and palms, the types of trees mentioned by the authors as constituting dense vegetation. Nonetheless, we obtained identical results: distance from sea and elevation alone account for the differences between hamlets in mortality or in loss of wealth (Table 1b, d).

Finally, we wondered if there was a strictly spatial component to mortality or loss of wealth. Hamlets with either high (or low) mortality may be closer to one another on average due to unconsidered environmental or social factors. Such spatial autocorrelation violates the independence assumption of parametric regression in that each dependent variate and its associated error term are correlated. Hence, we performed Mantel tests which assess the correlation (as standard Pearson product-moment coefficients) between the ith and jth entries of a matrix cataloguing pair-wise differences in, for example, hamlet mortality figures and the same entries of an identically constructed matrix of distances between hamlets (Mantel, 1967). Significance was assessed by randomly permuting the values of one of the matrices (Legendre, 2000) and re-calculating the correlation coefficient 10,001 times. We found no significant contribution to mortality from the spatial arrangement of hamlets ($r = -0.0634$, $p = 0.728$). However, hamlet arrangement was weakly and significantly associated with loss of wealth ($r = -0.260$, $p = 0.0114$). We suggest that sociological factors may explain this result. Affluent (or less affluent) hamlets may be closer to one another than expected by chance for economic reasons and, hence, were subjected to similar effects of the tsunami which, in turn, was mediated by topographic features occurring on average at length scales larger than that of hamlet separation.

We do not wish to argue that vegetation cannot in general mitigate damage from tsunamis. The pertinent question is how much protection can be expected from a particular vegetation type given a tsunami of a particular height at the coast. Towards this end the insurance industry has developed equations to estimate the potential inundation distance of a tsunami of a given height which specifically incorporates a roughness coefficient (n) for various terrestrial terrains including mud flats ($n = 0.015$), built up areas with high rise ($n = 0.03$) and forests ($n = 0.07$) (The Tsunami Risks Project, 2005). However, even the predictions of inundation distance based on these equations must be interpreted with caution because tsunamis rarely arrive as a single wave, rather, they typically occur in series known as wave trains (The Tsunami Risks Project, 2005). The tsunami generated by the earthquake of December 26, 2004 was composed of at least three main waves over much of its area (Lay et al., 2005). The effect of a series of waves can be much greater than that predicted on the basis of each wave arriving alone, because the first wave in the train will clear much vegetation and enable following waves to penetrate further than predicted on the basis of the wave height at the coast and the pre-existing vegetation. An excellent example of this effect was provided by the series of tsunamis that were generated following the eruption of Krakatoa in 1883. In this case, tsunamis that were estimated to have a wave height at the coast of 35 m penetrated up to 8 km inland through primary rainforest (The Tsunami Risks Project, 2005) much greater than the 2 km predicted from wave height and vegetation roughness coefficient. We see a genuine danger in overstating the protective capacity of vegetation, because it may lead to a false sense of security and eventually, when the next wave comes, to a lack of trust in science. Coastal vegetation, such as mangroves, can provide coastal communities with many valuable goods and services, and the protection of these ecosystems is an endeavor we wholeheartedly support, however, expecting these ecosystems to provide protection from large tsunamis appears, on the basis of our re-analysis of Kathiresan and Rajendran (2005), unrealistic.

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